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TECHNOLOGICAL PROBLEMS ANTICIPATED IN THE APPLICATION OF FUSION REACTORS TO SPACE PROPULSION AND POWER GENERATION

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16. Abstract

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SUMMARY

Mission and system studies have shown that fusion reactors potentially may be the most attractive energy source for space power and propulsion systems. Some methods by which fusion reactors may be applied to space missions are discussed. The problems posed by conversion of the thermal energy of the reacting plasma to electrical power and/or to an exhaust jet are considered, and their implications for research and development in the 1970's are reviewed. Recent analytical and experimental studies conducted at the NASA Lewis Research Center are reviewed, and their significance for the future direction of space-related fusion research are discussed.

INTRODUCTION

Very encouraging progress over the past five years has been reported in the field of controlled fusion research (ref. 1). Several basic problems that were thought to stand in the way of achieving energy densities and confinement times of thermonuclear interest have been circumvented or overcome. Some of the highlights of this progress include the reporting of radial diffusion rates substantially slower than the Bohm value (refs. 2 and 3); macroscopic stability of toroidal plasmas (refs. 2 and 3); successful demonstration of techniques for the feedback stabilization of a broad class of macroscopic instabilities, which are now available should such instabilities arise (ref. 4); and the demonstration that neither an energy density gradient (the free energy reservoir responsible for the hypothetical "universal" instability) nor small-scale fluctuations of

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*This is an expanded version of a paper presented at the fifth Intersociety Energy Conversion Engineering Conference, Las Vegas, Nevada, September 21-25, 1970.

the plasma properties necessarily imply a radial diffusion rate in excess of the classical value (refs. 2 and 3). These and other less notable results were deemed so encouraging that a conference on fusion reactor technology was held in Culham, England, during September 1969 (ref. 5). It was reported at this conference that economically competitive fusion reactors may be available for ground-based electrical power production by the 1990's (ref. 5).

In this climate of optimism and progress, it is appropriate to review and project space-related fusion research for the decade of the 1970's. The promise of fusion reactors for space power and propulsion systems was early recognized (refs. 6 and 7) and has recently been discussed and compared with other systems by Moeckel (ref. 8). These fusion systems would be assembled in earth orbit and operate only in deep space; would be used for round-trip manned missions to the planets or their satellites; and would accomplish their missions in times much shorter than those anticipated for other propulsion systems.

A typical solid-core fission rocket for these planetary missions might generate 10^5 pounds force (4.45×10^5 N) of thrust at an exhaust velocity of 10 kilometers per second. Such a reactor would have to generate about 5000 megawatts of power. A fusion reactor for the same mission would generate a minimum of about 200 megawatts. Such a reactor would operate at much lower thrusts and at the optimum exhaust velocity, about 10 times the velocity that can be achieved with materials-limited fission reactors. The amount of power required for space applications is about 10 percent that being discussed for individual ground-based power plants. A spaceship containing such a fusion propulsion system would have a typical initial mass of 10^6 kilograms, and would be appropriate to a period when large payloads must be moved to and from the planets.

A body of literature exists on the application of fusion reactors to space missions. A bibliography of these studies is given in the appendix. These studies indicate that fusion systems could have the following advantages for manned planetary missions:

(1) For a given payload mass, the initial mass in earth orbit and round-trip time are much smaller for fusion systems than for chemical systems, because the former can operate at the optimum exhaust velocity for the mission.

(2) The initial mass in earth orbit and round-trip mission time, for a fixed payload, are significantly smaller for fusion systems than for fission rockets or fission-electric systems. This comes about from the ability of fusion systems to operate at the optimum exhaust velocity for the mission; the possibility of direct conversion of plasma enthalpy to thrust or electrical power; and the reduced mass of moderating and shielding material possible if there is no requirement for neutron economy.

(3) If the D-D reaction can be harnessed for space applications, the fuel should be inexpensive enough to exhaust directly into space along with the propellant. Tritium and

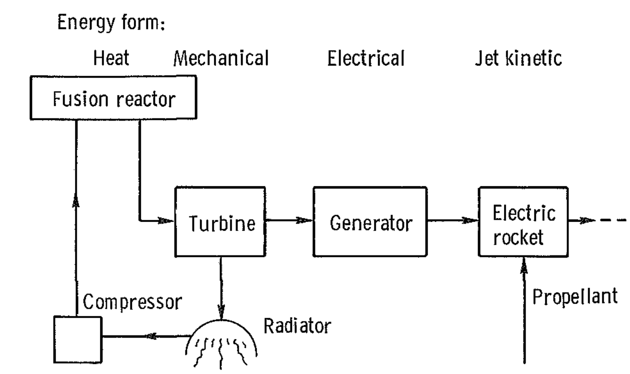
fissionable fuels will probably be too scarce or too expensive to allow the unused fuel to be lost to space.

The material discussed below is intended to apply to concepts utilizing steady state fusion reactors. However, much of the discussion below will also hold for pulsed fusion reactor concepts.

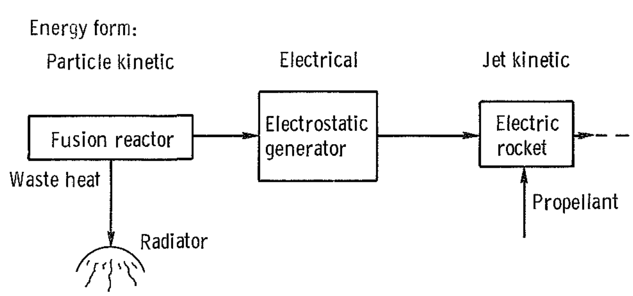
System Configuration

With the fusion reactor as power source, a variety of systems might in principle be employed to produce thrust. For example, figure 1 illustrates systems wherein electrical power can be generated and subsequently used to produce thrust in an ion engine or MPD thruster.

In figure 1(a) is shown a schematic of a fusion-electric propulsion system in which the fusion reactor is used as a source of heat energy, which is then converted by a Carnot cycle to electrical power. The fusion reactor merely replaces the fission reactor in a fission-electric propulsion system. This concept has many of the drawbacks of



(a) Heat cycle.



(b) Direct conversion.

Figure 1. - Fusion-powered electric propulsion systems.

fission-electric systems, including a relatively high mass-to-power ratio and a Carnot efficiency limited by the melting point of solid components of the reactor-generator system.

A somewhat simpler and more elegant system is shown in figure 1(b), in which the charged particles from the reactor are used directly to produce electrical power. In such a system (see Post ref. 9), the charged reaction products that escape from the confining magnetic field impinge on collecting electrodes, thus generating electrical power directly.

The simplest and most elegant application of fusion reactors is shown schematically in figure 2, in which the escaping plasma is mixed with additional propellant and ex-

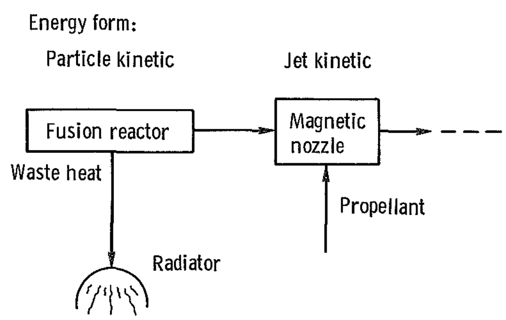
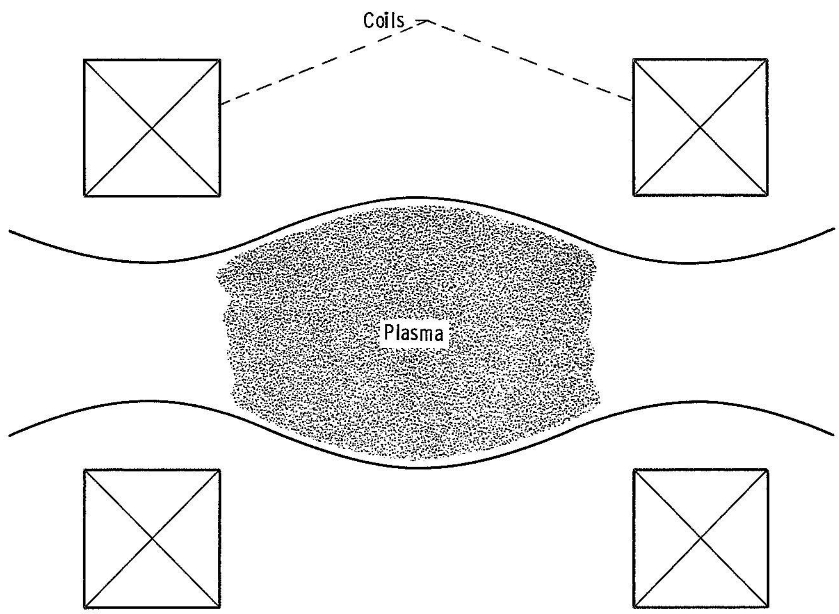


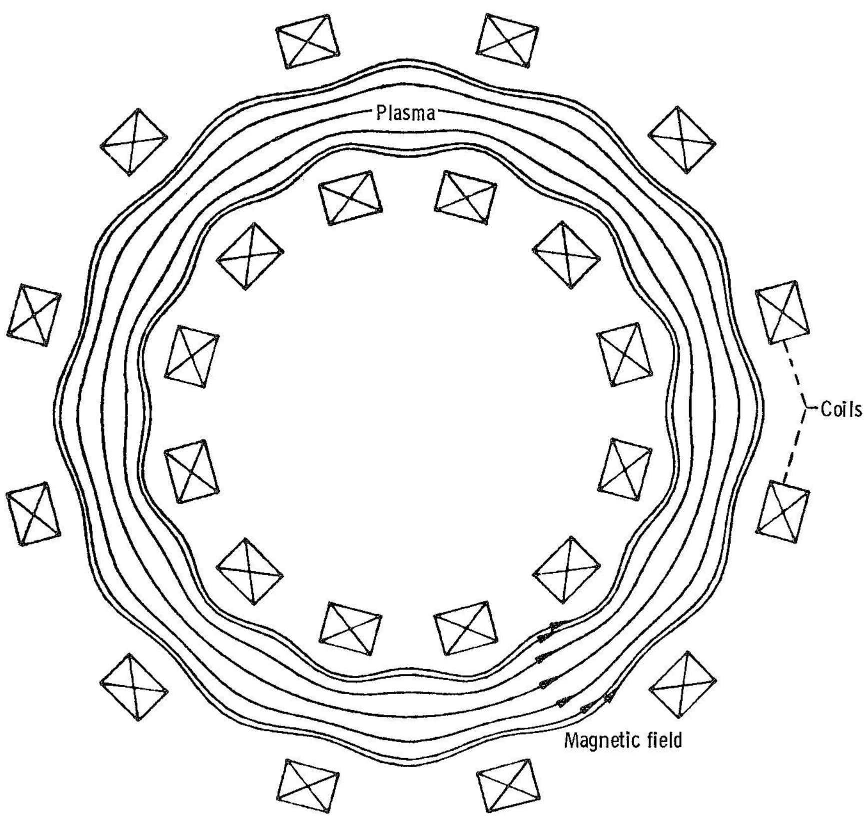
Figure 2. - Fusion rocket system: hot plasma efflux accelerates propellant in magnetic nozzle.

hausted in a magnetic nozzle to provide thrust. This arrangement constitutes a direct fusion rocket, similar in principle to a chemical rocket, but utilizing nuclear rather than chemical combustion. Such a fusion rocket should be the ultimate form for nuclear space propulsion, since nuclear energy is directly available for thrust, without massive intermediate energy conversion equipment. Gaseous core nuclear fission rockets may have similar advantages, but with several disadvantages not found in fusion systems. These disadvantages include the necessity of neutron economy, separation of the fissionable fuel and propellant, and safety hazards associated with a critical mass of gaseous fissionable fuel. In addition, their exhaust velocity is limited by a need to operate at high pressure, and by the requirement that energy be transferred to the propellant by radiation.

Fusion reactors will utilize one of two basic magnetic field geometries shown schematically in figure 3. In figure 3(a) is shown an open-ended system, in which the plasma is confined in a region of weak magnetic field between two strong "magnetic mirrors." By making one magnetic mirror much stronger than the other, it is possible to promote the loss of the plasma through the weaker mirror. This class of magnetic



(a) Open configuration.



(b) Closed configuration.

Figure 3. - Magnetic field configurations for plasma confinement.

field geometries has the serious disadvantage that the plasma losses along the magnetic field lines, and out the mirrors, are very large, perhaps too large to permit a net-power-producing fusion reaction to take place (ref. 5).

The second major class of magnetic field geometries is the "closed" or toroidal geometry in which the plasma is confined on magnetic field lines that close on themselves in a toroidal volume. This geometry is subject to radial diffusion losses, which have recently proven to be substantially smaller than the end losses suffered by open-ended systems. In recent years there has been a growing consensus that toroidal geometries are most promising for fusion reactors (refs. 1 and 5). Future developments may alter this picture substantially, but at present it appears probable that space-borne fusion reactors will be of a toroidal configuration.

COMPARISON OF SPACE AND GROUND-BASED SYSTEMS

Problems Common to Both Systems

Because it is not our purpose to review the problems of fusion research per se, the problems common to both space and ground-based fusion reactors are listed with brief comments. These can be divided into problems of basic physics and of engineering. Some of the common problems of basic physics include the following:

(1) Injection of plasma into confinement volume

(2) Stability of plasma on microscopic scale

(3) Heating of plasma to thermonuclear conditions

(4) Net energy production from reactor

(5) Minimizing radial diffusion of plasma

(6) Minimizing cyclotron radiation from plasma

Injection of fuel into the interior of a fusion reactor is not a trivial problem; it has been estimated that a rifle bullet fired into a reactor plasma would experience such an enormous energy flux that it would vaporize and be ionized before traveling its own length (refs. 10 and 11). This injected material would be trapped on magnetic field lines, and not penetrate to the interior of the plasma. Injection of fuel may require pellets of deuterium ice accelerated to velocities of tens of kilometers per second (ref. 5). The problems of radial diffusion and stability of plasma appear on the way to solution as a result of recent research (refs. 1 and 4). The problems associated with plasma heating and maximizing the fusion reaction rate will probably dominate fusion research in the 1970's, just as stability and radial diffusion have been the focus of research in the 1960's.

Some of the engineering problem areas common to space and ground-based fusion reactors include the following:

(1) Further development of superconducting magnet technology

(2) Development of a long-lived first surface material

(3) Removal of heat flux from the first surface and the protective blanket for superconducting coils

(4) Development of a suitable blanket to shield superconducting magnets from the neutron flux

(5) Conversion of plasma enthalpy to electrical power for onboard and propulsion system use

(6) Radiation damage of wall materials by neutron flux

At this time, it appears virtually certain that superconducting coils will be used to generate the magnetic fields required to confine the reacting thermonuclear plasma. Existing superconducting materials require a liquid-helium temperature environment, which must be shielded both from the radiant energy flux from the plasma, and also from the heat load associated with the neutron flux. Space applications of superconductive magnet technology will be more demanding than ground-based applications, because of the mass minimization constraint.

Problems More Important to Ground-Based Fusion Reactors

In general, developing a successful fusion reactor space applications will be more difficult than developing a similar ground-based reactor for electrical power generation. However, there are some problems of ground-based fusion reactors that may be simplified or eliminated in space applications. These problems include the following:

(1) Ground-based fusion reactors must compete with other electrical power generating systems on an economic basis. As a consequence, the development of fusion reactors for ground-based power generation is likely to be retarded or stymied by very small unfavorable differentials in the unit costs of capital equipment (ref. 12).

(2) Safety considerations alone will require the complete shielding and absorption of the flux of radiant energy and neutrons from ground-based fusion reactors. In addition, neutron economy will be required for tritium breeding in such reactors if the D-T reaction proves to be the only feasible system. If the D-D or D-He^3 reactions prove to be capable of producing a net power output, it may be unnecessary in space applications to conserve either the neutrons or their energy. The design of the superconducting coils and shields should then be such as to maximize the fraction of neutrons that escape freely to space. If the cyclotron radiation turns out to be unimportant to the energy balance of the plasma, this too can be reflected from the coil structure and channeled to

space. If either the neutrons or the radiant energy is reflected to space, it will be possible to reduce the amount of massive equipment otherwise required to absorb and reradiate the energy flux from these sources.

(3) The maintenance of a vacuum environment for the reacting plasma will be a major item of capital costs and a constant threat to the uninterrupted operation of ground-based fusion reactors. Since presently envisioned fusion propulsion systems will be limited to orbit-to-orbit missions because of their low thrust-to-mass ratio, a vacuum environment will be available at all times.

Problems More Important to Space Applications

There exists a large class of foreseeable problems that are either unique to space applications of fusion reactors, or are crucial for the success of such applications. Many of the problems of basic physics stem from the fact that the D-T reaction does not appear promising for space applications. Currently envisioned ground-based fusion reactors are expected to operate on the D-T reaction and simply produce a net power output (refs. 1 and 5). Such reactors will, in all probability, have massive and complicated subsystems for injecting energetic plasma, and for the breeding and recovery of tritium. These subsystems tend to rule out the D-T reaction for space applications.

Some of the problems of space fusion reactors are as follows:

(1) In order to eliminate systems for the injection of energetic plasma, space-borne fusion reactors must be self-sustaining as well as capable of producing net power; that is, the charged reaction products must be capable of heating neutral fuel injected at ordinary temperatures to temperatures high enough to produce at least one further fussion reaction.

(2) The neutrons produced in fusion reactions will not contribute directly to heating the reacting plasma, while the slowing-down of charged reaction products will. The energy of the neutrons will either be lost directly to space, or must be absorbed by the structure and reradiated to space by cooling systems. It is therefore desirable to minimize the production of neutrons from the reaction, and to maximize that of charged particles. The D-T reaction is unsatisfactory from this standpoint, since about 80 percent of the reaction energy is carried away by neutrons. Although the D-D reaction has somewhat more favorable reaction cross sections at low plasma kinetic temperatures, the D-He^3 reaction seems the most attractive candidate for space applications, and has been given the most attention in the analyses cited in the references. Although the D-He^3 reaction will produce some neutrons from concurrent D-D reactions, the neutron flux will be many times smaller than from either D-D alone or D-T. In addition, a further reduction can be expected if the reactant proportion is altered from 50 percent each to

an excess of He^3. Other factors being unchanged, the intensity of the side D-D reaction could be reduced by a factor of 2 by going to a ratio of 65 percent He^3 and 35 percent D (ref. 13). This estimate disregards possible changes in bremsstrahlung accompanying the increased concentration of nuclei with higher atomic numbers, so that the total benefits might not be so great.

(3) The contemplation of the D-He^3 reaction for space applications suggests other problems. First is the probability of higher reaction temperatures than would be needed for the ground-based systems. Englert (ref. 13) has shown that this, in turn, will cause an altered balance in the system energetics - the ratio of ion to electron temperature, the energy flow from the reaction products to ions and electrons, the buildup of alpha particles in the reaction volume, and the intensity of bremsstrahlung and synchrotron radiation. All these factors need a more careful evaluation than has yet been given them.

(4) If direct conversion to electrical energy or thrust, illustrated in figures 1 and 2, is utilized, a method must be developed to control the ions escaping from the plasma. Their velocity vectors must be made unidirectional through manipulation by electric and magnetic fields. This unidirectional beam can then be used for direct conversion to electrical power, or for the exhaust jet of a rocket.

(5) The charged reaction products lost from a self-sustaining D-D or D-He^3 reactor will consist of these species, with a small admixture of tritium, protons, and He^4. In a self-sustaining fusion reactor, the charged reaction products would be at the operating temperature of the reactor, in the range of from 40 to 100 keV. The velocities of these species in this range of kinetic temperatures is about a factor of 10 higher than the optimum propellant velocity required for interplanetary missions (refs. 6 to 8, and 13). Mixing of the beam of escaping charged particles with a 10:1 ratio of propellant gas is therefore required for optimum performance. Studies of this propellant mixing problem (ref. 14), have shown that propellant injected into the beam of escaping ions can raise the average momentum of the exhaust jet to the desired values. This mixing problem is a crucial one for fusion rockets, and further experimental studies of relevant cross-sections and the entrainment of neutral gas by plasma beams appears desirable.

(6) A suitable heat-transfer method must be developed to carry heat away from the superconducting coil shields, and for use in the generation of electrical power for on-board and propulsion system needs. Problems of this nature are considered in the magnetocaloric power generating cycle discussed in the section Novel Systems for Cooling and Generation of Electrical Power.

Many of the engineering problems associated with space-borne fusion reactors are similar in kind to those associated with space application of fission rockets and fission-

electric propulsion systems. Many of these common problems are under study for application to fission systems, and include the following areas:

(1) Development of lightweight components throughout

(2) Development of an energy conversion system for electrical power needs

(3) Development of a heat-transfer and radiation system for waste heat

Other engineering problems are more or less unique to space-borne fusion reactors, and would have to be approached ab initio for this application. Such problems include the following:

(1) A lightweight liquid-helium refrigerator must be developed to extract and reject heat leaking into the superconducting coils.

(2) Special consideration must be given to cryogenic cooling in a near-zero-gravity environment. In zero gravity, bouyancy forces no longer exist to remove gas bubbles from around the superconducting wire, and to maintain a stable liquid-vapor interface. Special fluid-dynamic and heat-transfer designs will be required for cryogenic cooling of superconducting magnets in space.

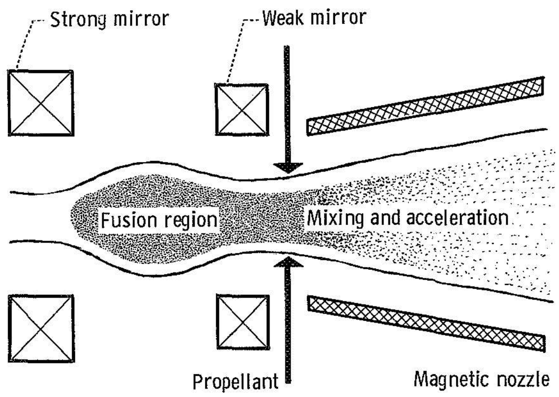
(3) A lightweight system is needed to provide a repeated startup capability in space. Such a system may have to provide electrical power comparable to the steady-state output of the fusion reactor - at least several hundred megawatts - for a period of time comparable to the individual ion confinement time, on the order of 1 second. One possible concept for the source of such startup power is a chemically powered magnetohydrodynamic (MHD) generator, which produces a large pulse of electrical power over the duration during which a charge of chemical propellant burns. Such systems need not be very massive. For example, the combustion of only 100 kilograms of hydrogen and oxygen would produce 1000 megawatt-seconds of energy. Converting such energy into a form usable for startup will, of course, add mass to the system.

CONCEPTS FOR SPACE APPLICATIONS OF FUSION REACTORS

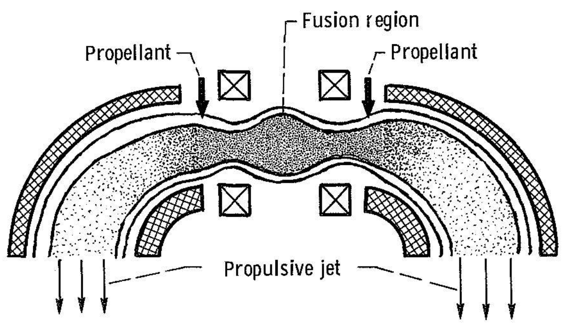
The problems discussed in the preceding section, associated with space applications of fusion reactors, may be approached in a variety of ways. Some of these approaches are discussed herein.

Direct Production of Thrust from Fusion Reactors

Direct conversion of the reacting plasma energy to thrust should involve the minimum propulsion-system mass/power ratio, and is therefore most desirable. Such direct conversion might be accomplished in open-ended mirror systems by one of the



(a) Single-ended open system: predominant particle loss occurs through weaker mirror.



(b) Double-ended open system: losses through both mirrors used to produce thrust.

Figure 4. - System for direct production of thrust from open magnetic configurations.

two arrangements shown in figure 4. Figure 4(a) illustrates the use of an asymmetrical magnetic mirror, in which one mirror is much stronger than the other. The charged particles would flow preferentially out the weak mirror, and through a guide field where the departing plasma is mixed with neutral propellant gas to obtain the optimum exhaust velocity. The plasma escaping through the stronger mirror could be used for direct conversion to electrical power for onboard needs. In figure 4(b) is shown a symmetrical magnetic mirror machine, in which the plasma leaking out both ends is turned through 90° by a magnetic guide field, in which the propellant mixing takes place.

The direct production of thrust from toroidal geometries presents additional problems, since there is no single hole in the magnetic field through which the bulk of the plasma will be lost. Space-borne fusion reactors will require the simplest possible magnetic field geometry, in order to conserve mass and to reduce to an absolute mini-

mum the thermal energy intercepted by the reactor structure. The relatively complicated conductor configurations used to stabilize present-day toroidal plasma are undesirable. An attractive possibility for space applications is the "bumpy torus" geometry, originally proposed in reference 15 and illustrated in figure 3(b). This consists of simple current loops placed in a toroidal array, and allows significant apertures for escape of neutrons and radiant energy to space. If stabilization of macroscopic plasma instabilities proves necessary, this might be accomplished by dynamic or feedback stabilization.

The plasma will escape from the bumpy torus geometry of figure 3(b) by radial diffusion. This radially escaping flux can be skimmed off the outermost drift surfaces and manipulated into a unidirectional beam by a device similar to the Princeton "divertor" (ref. 16), or by a modified, time-reversed version of the electron injection scheme used for entropy trapping in the original bumpy torus apparatus (ref. 17). One conceptual approach to the problem is shown schematically in figure 5. The escaping

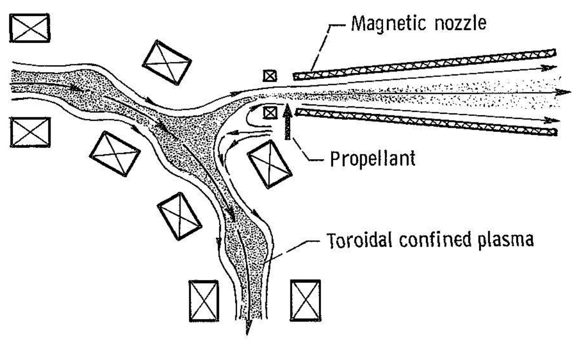
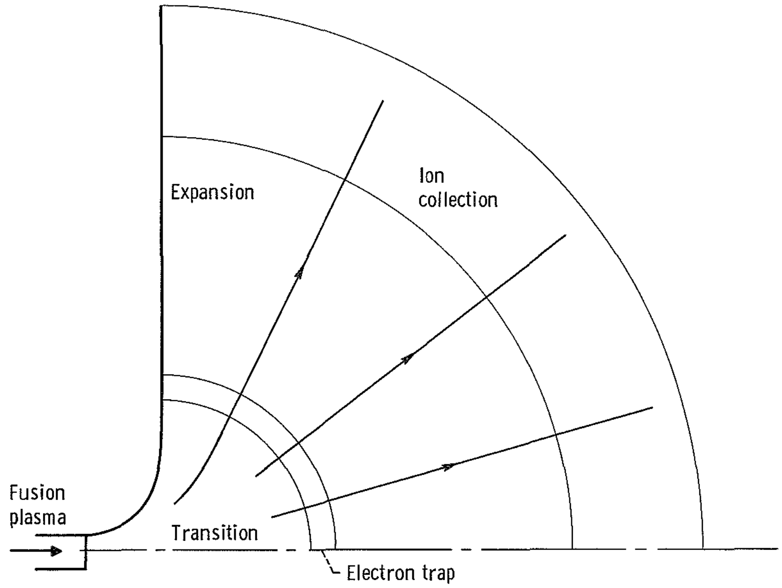


Figure 5. - System for direct production of thrust from closed magnetic configuration.

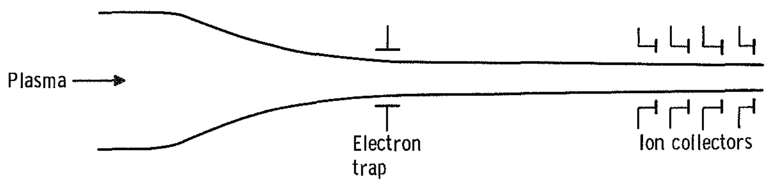
plasma in this unidirectional beam can be mixed with additional propellant gas to obtain the optimum exhaust velocity.

Direct Production of Electrical Power

A novel concept for the direct conversion of the plasma enthalpy to electrical power is that proposed by Post (ref. 9) and illustrated in figure 6. As shown in this figure, the escaping plasma is manipulated into a fan-shaped beam by the diverging magnetic field from a confinement geometry. The beam density is then decreased by expanding the beam width in the plane normal to the diagram, until the Debye distance is comparable to the beam thickness. The beam is then passed between two negatively charged



(a) Top view.



(b) Section (width enlarged).

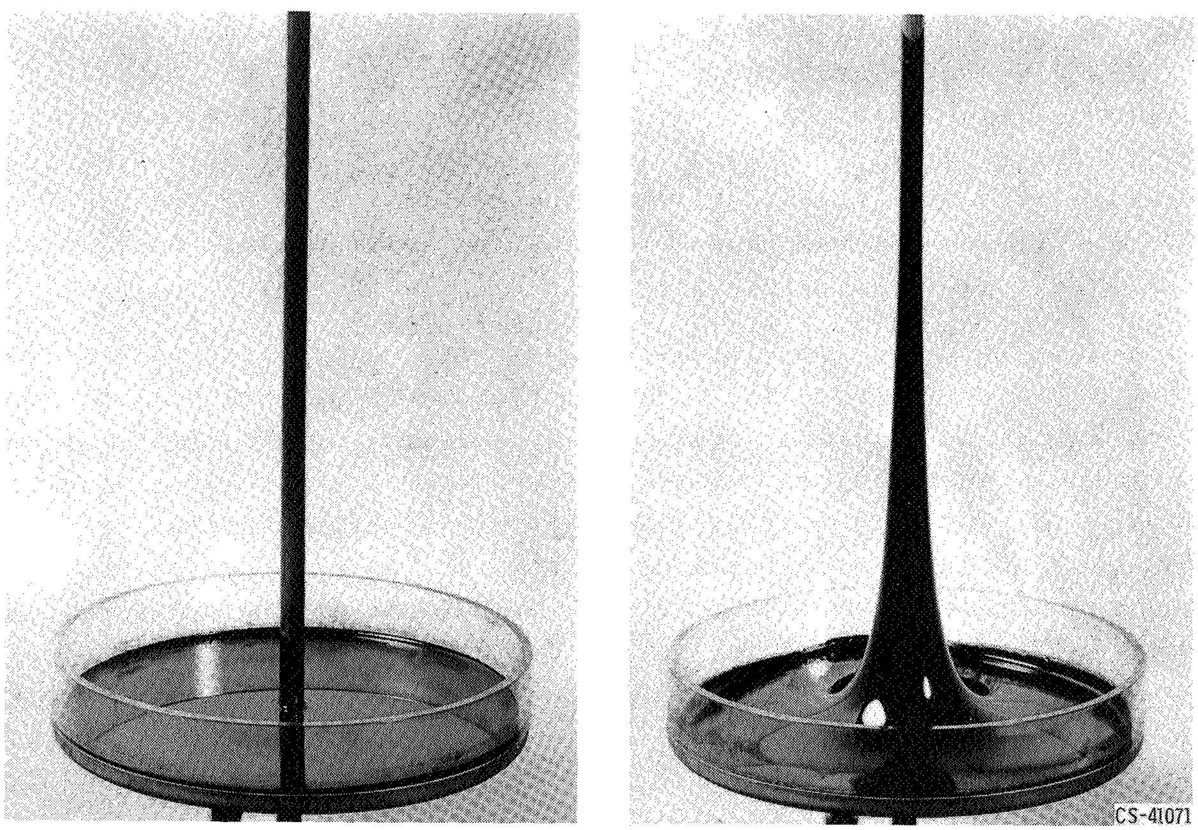
Figure 6. - Direct conversion concept: hot plasma efflux from fusion reactor guided from round beam to thin, flat beam and field strength reduced; electrons removed; ions decelerated and collected.

electrodes which collect or reflect the electrons back into the containment volume. The ion beam then proceeds adiabatically into a region of weaker magnetic field in which the transverse components of ion velocity are converted into velocity along the magnetic field lines. The ions lose energy to the electric field, and then impinge on a series of electrodes at potentials comparable to the ion energies. The ions do work in moving along the electric field between the negative and collecting electrodes; they can be made to arrive at the collecting electrodes with little or no residual energy. The probable size and weight of such a direct conversion apparatus may be excessive for space application. Perhaps it could be combined with the radiator. In any case, further analysis is needed of this and other approaches to direct conversion for thermonuclear systems.

Novel Systems for Cooling and Generation of Electrical Power

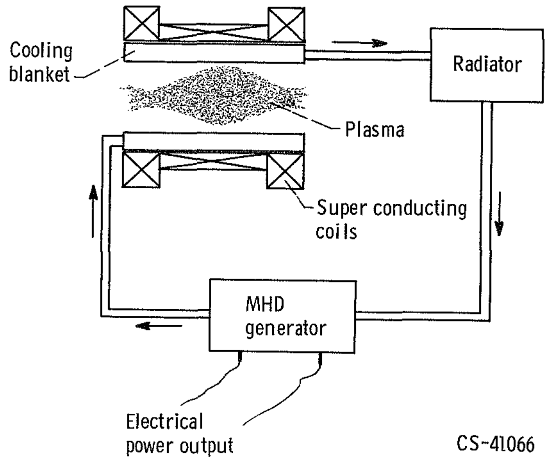
In space-borne fusion reactors, it will be necessary to remove large amounts of heat from the first surface and from the shielding blankets which surround the superconducting coils, and to transfer this heat energy to a space radiator and/or to the propellant. Heat pipes are one promising concept for such heat removal. Pumping of the cooling fluid, and perhaps power generation as well, may be possible with a magnetocaloric cycle (refs. 18 and 19).

A magnetofluid is ferromagnetic at ordinary temperatures and is strongly attracted to regions of high magnetic field. This magnetic attraction is illustrated in figure 7(a), which shows a dish of ferrofluid surrounding a wire. When a current flows, the magnetic field attracts the ferrofluid up the surface of the wire. If the magnetofluid is heated to its Curie temperature while in a strong magnetic field, the magnetic field no longer attracts it, and a pressure head results. This pressure head can be used to pump the fluid between a hot region in a strong magnetic field and a radiator in a weaker magnetic



(a) Dish of ferrofluid surrounding wire. When current flows, as on right, magnetic field attracts fluid up wire. (Photo courtesy of R. E. Rosenweig.)

Figure 7. - Application of ferrofluids to power generation.



(b) Schematic of thermonuclear power system using magnetocaloric cycle.

Figure 7. - Concluded.

field, as shown in figure 7(b). If the magnetofluid is a liquid metal, it can be made to flow across the magnetic field and generate electrical power. Successful magnetofluids based on finely divided iron suspended in kerosene have been demonstrated (refs. 20 to 22), but liquid-metal magnetofluids usable in fusion reactor applications remain to be developed.

Shielding of Superconductive Coils

Studies have been made of the shielding requirements of superconductive coils in ground-based fusion reactors based on the D-T reaction (refs. 23 and 24). These studies show that blanket thicknesses of at least 1 meter will be required, most of this for the tritium breeder blanket. As previously stated, the enormous mass of such blankets, and the necessity of surrounding the entire plasma to get favorable tritium breeding ratios, virtually rules out the D-T reaction for space applications. If the D-D or D-He^3 reaction were used, the coils could be surrounded by a neutron reflector, like that shown in figure 8. This figure represents schematically a two-coil sector of a 12-coil bumpy torus magnetic field. The basic design philosophy of such an arrangement would be to reflect as much radiant energy and as many neutrons as possible into space, so that their thermal energy will not have to be dealt with. Most of the neutrons that get past the reflecting material would be moderated and absorbed before they could reach the liquid-helium environment around the coils. The thermal energy appearing in the shield would be removed by the magnetocaloric cycle, by heat pipes, or by con-

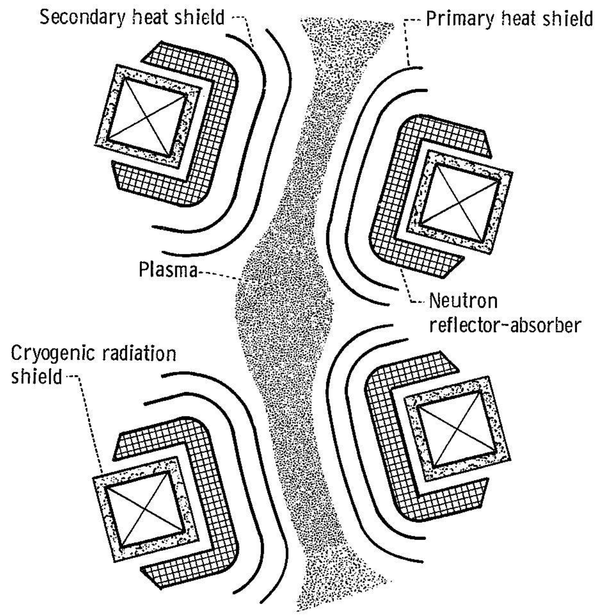


Figure 8. - Shielding components needed for superconducting coils in space fusion system.

ventional heat-transfer systems. The first surface would have a high reflectivity, in order to reflect the longer wavelength radiant energy into space as well. Such a reflecting shield should be much lighter than the tritium breeder shields required for ground-based fusion reactors. Even with shields and baffles, the heat leak to the superconductive coils must be removed. This may be accomplished if the liquid-hydrogen (or deuterium) propellant is available as a heat sink for the refrigerator (ref. 13). The refrigerator mass may become prohibitive if the heat flux carried by the neutrons is too large, or is not enough propellant is available as a heat sink.

STATUS OF SPACE-RELATED FUSION RESEARCH

A modest effort is underway within NASA to identify and explore crucial problems, with long lead times, which stand in the way of space applications of fusion power. This work at present includes systems and mission studies to identify the potential of fusion power for space applications; development of superconducting magnet technology required for fusion and other advanced space energy conversion systems; and two experimental approaches to the problem of plasma heating and confinement (ref. 25).

Systems and Mission Studies of Fusion Propulsion

As the present stage of development of controlled fusion, systems studies for fusion rockets necessarily rest on a shaky foundation of assumptions. Such studies are useful in two ways: First, unless reasonable assumptions result in a forecast of very substantial gains over alternative systems, what would probably be an unprofitable line of investigation can be abandoned. Second, the analysis can identify which assumptions are most critical to the outcome, thus showing which additional information will most improve the reliability of the results.

A system study of a fusion rocket has been performed by Englert (refs. 13 and 14), who assumed an open magnetic configuration and included calculations of methods for dealing with the heat load to the liquid-helium-temperature superconductive magnets. Later analysis (ref. 14) of the mixing process - energetic escaping plasma mixing with hydrogen propellant - showed the feasibility of direct acceleration of the propellant inside a magnetic nozzle. System specific mass approaching 1 kilogram per kilowatt of jet power was obtained, at specific impulses of the order of a few thousand seconds. Using such values for the system, Moeckel (refs. 8 and 25) obtained significant improvement over other propulsion systems in orbit-to-orbit round-trip mission times to other planets. Results for a Mars mission are shown in figure 9. Even more favorable results were reported (refs. 8 and 25) for missions to the outer planets.

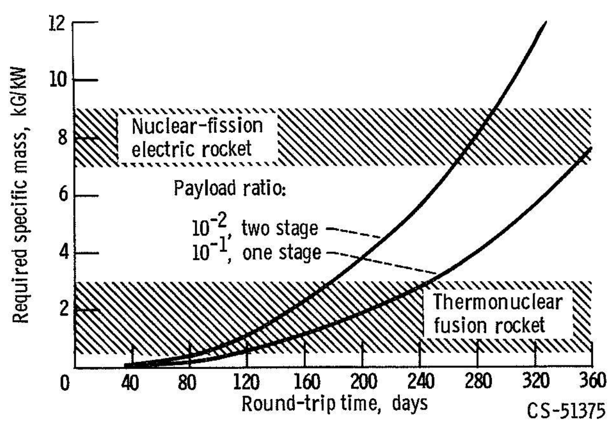


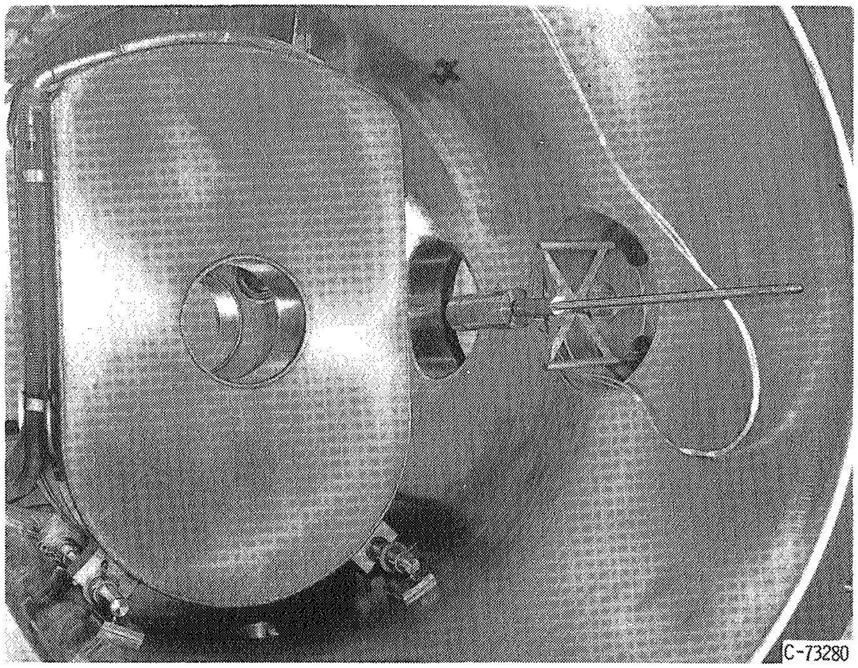
Figure 9. - Time required for Mars round trip as affected by propulsion system characteristics.

Superconductive Magnet Technology

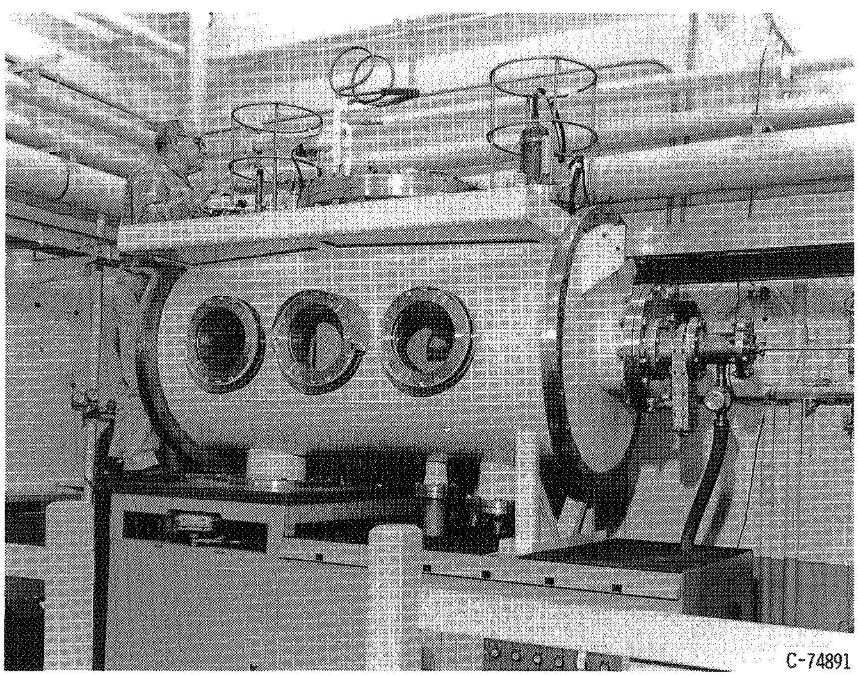
Several advanced propulsion systems other than fusion reactors will require the high magnetic fields and low power consumption afforded by superconductive coils. NASA has accordingly supported the development of superconductive magnet technology, with the very encouraging results reported by some of our colleagues (refs. 26 and 27). One of the results of this work is shown in figure 10, a set of four superconductive coils

Figure 10. - Four 51-centimeter-bore superconducting magnets.

that together will achieve 5.9 tesla on the axis of its approximately 51-centimeter-diameter bore, when operated below the lambda point of liquid helium. These magnetic field characteristics are within a factor of 2 in magnetic field strength, and within a factor of 2 to 5 in diameter, of those envisioned for eventual fusion reactors. This work has also produced a 15-centimeter inside diameter superconductive coil that will produce 15 tesla on its axis (refs. 25 to 27). No problems have arisen in the course of this work which would imply any particular roadblocks in the way of scaling such magnets up to the size



(a) Veiw of superconductiong magnet dewars through open end of vacuum tank.



(b) Overall veiw of facility.

Figure 11. - Superconducting magnet facility used in plasma research.

required for fusion reactors. However, current practice in these superconductive magnets involves the use of substantial proportions of normal conductors paralleling the superconductors for stabilization. Thus the effective current density is much less than would be anticipated for the superconductor alone. Other methods for minimizing the mass of such stabilizing material are being studied (ref. 25). Current densities greater than 10^5 amperes per square centimeter are desirable for space applications.

The first superconductive magnet facility to be used for plasma physics and controlled fusion research went into service at the NASA Lewis Research Center in December 1964 (ref. 28). This facility is shown in figures 11(a) and (b). It is a magnetic mirror apparatus, each coil of which can generate up to 2.5 tesla on the axis of its 18-centimeter-diameter bore. This magnet facility has completed 5 years of satisfactory service without degradation of coil performance.

Modified Penning Discharge

The modified Penning discharge is one of two experimental approaches to fusion-related plasma problems at the NASA Lewis Research Center (refs. 29 to 31). The plasma produced in this discharge is shown in figure 12. The vertical element in the

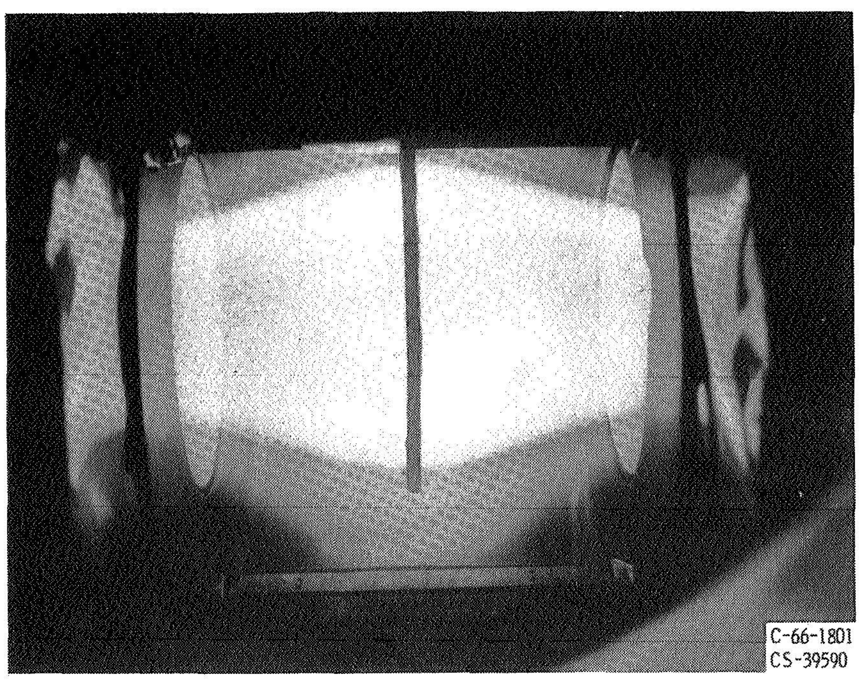


Figure 12. - Modified Penning discharge in superconducting magnetic mirror facility. Anode ring (vertical element in center) operates at high positive potentials.

center is the anode ring, which is operated at a positive potential of several tens of kilovolts. The energy of the deuterium ions escaping from the magnetic mirrors was studied as a function of the anode voltage and background pressure, with the result shown in figure 13 (ref. 31). The ion kinetic temperature is directly proportional to the anode voltage for each pressure, up to the limit of the power supply used, suggesting that ions of higher energies can be obtained by going to a sufficiently high anode voltage. The ion velocity distribution was found to be Maxwellian, and the electron energies were much lower than those of the ions. Both of these characteristics are very desirable in fusion

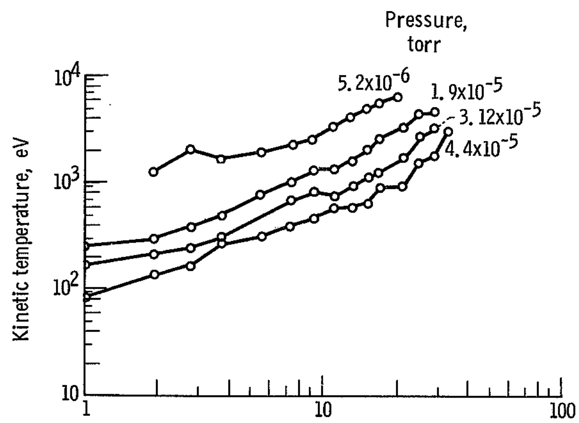


Figure 13. - Deuterium ion kinetic temperatures obtained in modified Penning discharge at various background pressures. Maximum magnetic field, 2 tesla.

applications; the Maxwellianization of the ion velocity distribution implies one less free energy reservoir to drive macroscopic and microscopic plasma instabilities; and it is desirable to dump the power supply energy into the ions rather than the electrons.

The best temperatures, densities, and confinement times observed simultaneously in this experiment thus far are as follows:

Ion kinetic temperature, keV	5
Electron kinetic temperature, eV	200
Plasma number density, per m^3	2×10^{16}
Ion confinement time, μsec	27

The ion and electron energies are quite promising, but the densities and confinement times are low as a consequence of end losses out the magnetic mirrors. These losses can be eliminated, and the density and confinement times increased, by using the modified Penning discharge in a bumpy torus configuration like that shown in figure 14. Such a magnetic field configuration, with twelve 3.0-tesla superconducting coils each with an

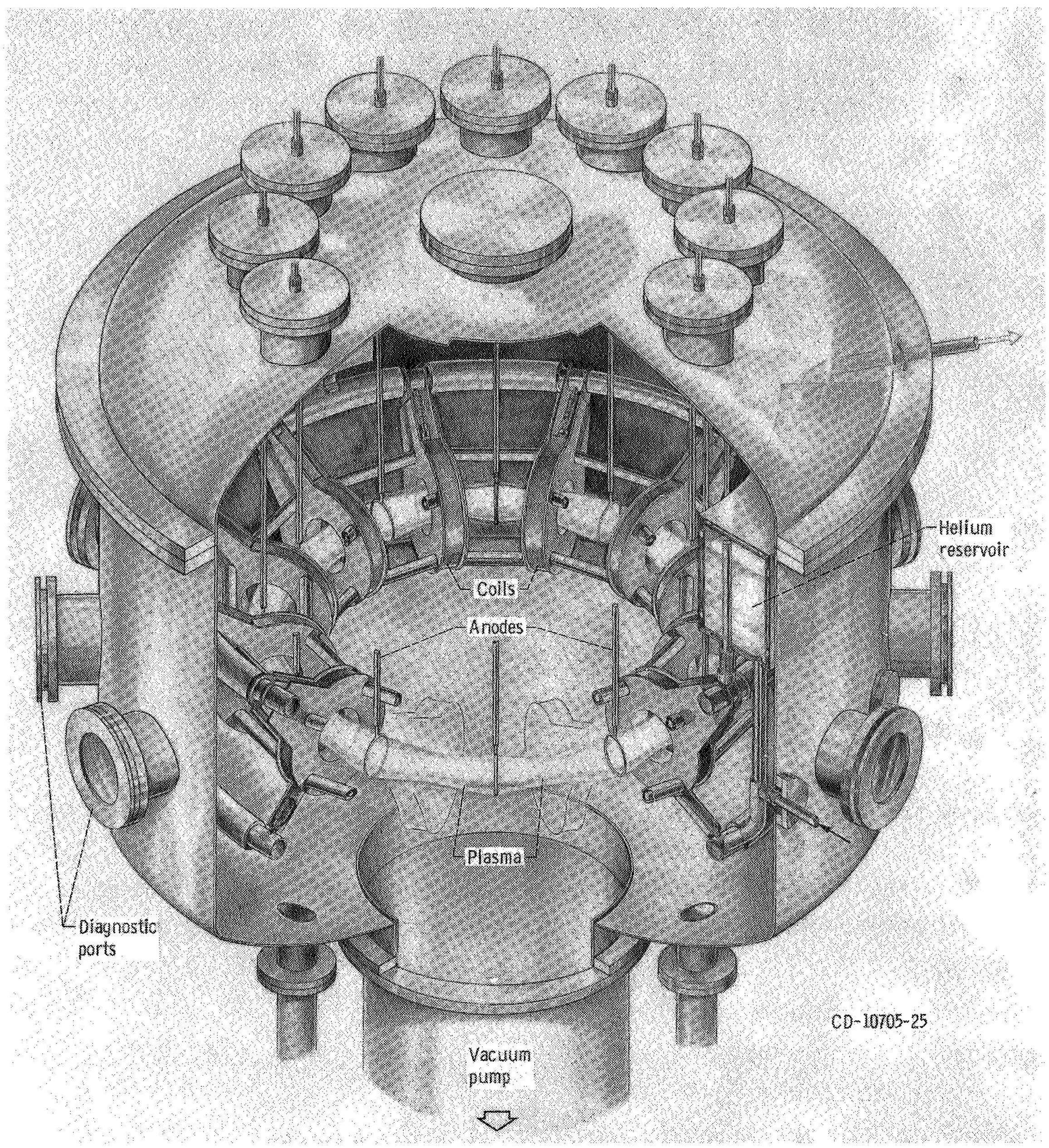
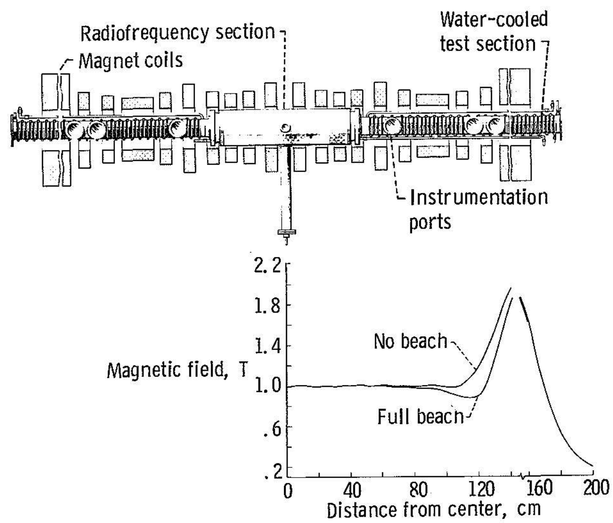
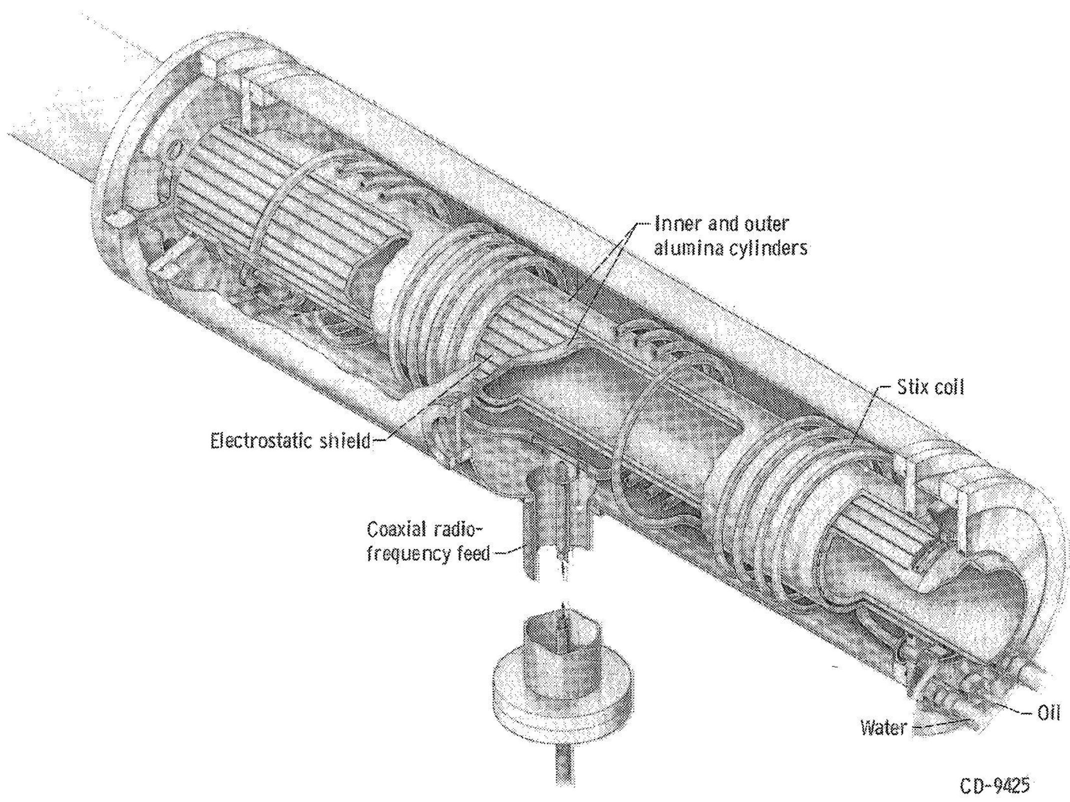


Figure 14. - Cutaway view of proposed bumpy torus facility. Magnetic field, 3 tesla on coil axes; plasma major diameter, 150 centimeters; plasma minor diameter, ~15 centimeters.



(a) Overall view with magnetic field shown.



(b) Cutaway view of center section showing radiofrequency (stix) coil and shielding.

Figure 15. - Experimental apparatus for study of plasma heating by ion cyclotron resonance.

inside diameter of 17 centimeters, is under construction for future use in this experiment.

Ion Cyclotron Resonance Heating

Another example of high-temperature plasma physics research at NASA Lewis Research Center is the ion cyclotron resonance heating (ICRH) program (refs. 25, 32, and 33). This heating scheme uses radiofrequency power to heat plasma ions in a steady-state manner. A schematic of the ICRH experiment is shown in figure 15(a). A specially designed radiofrequency coil, shown in figure 15(b), is located at the center of the system. This coil generates ion cyclotron waves which propagate axially away from the center section to the ends of the discharge chamber. The confining magnetic field near the ends is adjusted so that the ion gyrofrequency of the plasma is equal to the ion cyclotron wave frequency. Under this resonant condition, the ions rapidly absorb energy from the radiofrequency electric fields of the ion cyclotron wave.

The objectives of this research are (1) to assess the potential of the ICRH process for achieving fusion conditions; and (2) to develop a good research tool that produces a hot, dense plasma which can be used to study some of the basic problems in fusion research. Both theory and experiment indicate that radiofrequency power can be efficiently coupled to ion cyclotron waves in the plasma. The conversion of ion cyclotron wave energy into ion energy is presently under investigation in this experiment.

While operating in the steady-state, ion temperatures of 550 eV have been achieved in a plasma of 10^{18} m^{-3} density (ref. 32). A graph of ion energy as a function of axial position, taken with diamagnetic loops, is shown in figure 16. Limitations to this heating scheme have become apparent. First, the coupling efficiency from the coil to ion cyclotron waves is reduced as the plasma ion temperature increases (ref. 33). Second, only a small percentage of the power coupled into ion cyclotron waves is at present converted into ion thermal energy. Theoretical explanations for these limitations have been suggested, and ways of avoiding them are under investigation. These limitations and those of other heating methods may imply that more than one heating method will be necessary to raise plasma to thermonuclear conditions. In spite of these limitations, ion cyclotron resonance heating has produced a hot, dense, steady-state plasma which is, in itself, a valuable fusion research tool. Ion cyclotron resonance heating may be useful for reactor startup in space, even though, as previously noted, any continuous use of large amounts of power seems nonfeasible.

A major objective of our future plans is to apply ICRH to open-ended magnetic wells. One purpose of these tests will be to study experimentally the generation, propagation, and damping of waves in the more complex magnetic fields of these wells. Another

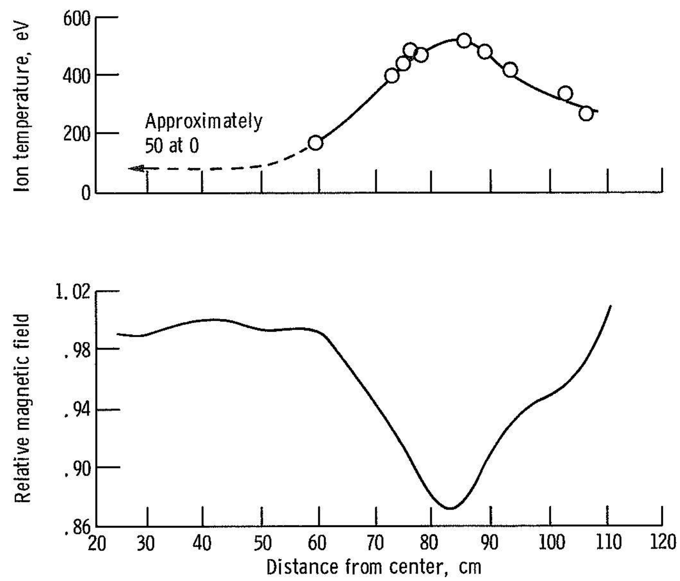


Figure 16. - Ion temperatures resulting from ion cyclotron resonance heating. Measurements in region of magnetic beach.

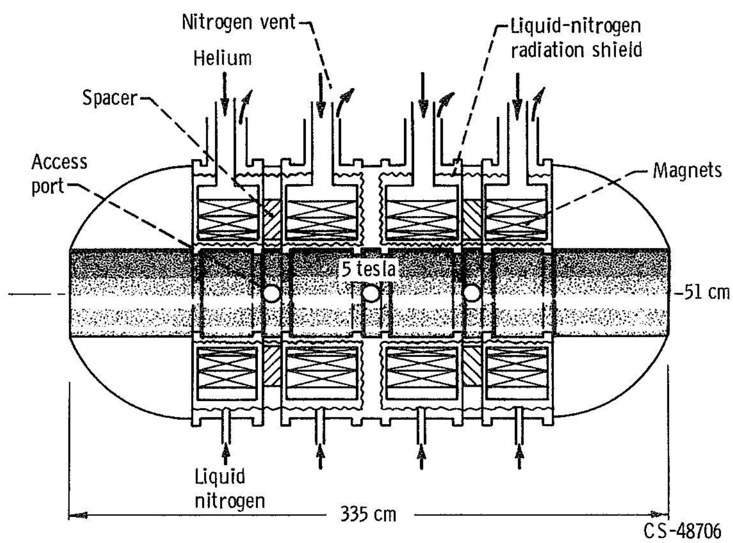


Figure 17. - Proposed superconducting magnetic mirror facility.

reason for applying ion cyclotron resonance heating to open-ended magnetic wells is to perform plasma stability studies in the regime of high ion density and temperature. Theory predicts that the so-called velocity space instabilities will occur at high densities in mirror machines. An experimental study is planned for a superconductive magnetic mirror apparatus, shown in figure 17, which will be capable of producing magnetic fields up to 8 tesla over a 51-centimeter-diameter bore.

DISCUSSION AND CONCLUSIONS

Many of the foreseeable problems associated with space and ground-based applications of fusion reactors appear to be common to the two applications, while some are unique to the respective application. A similar degree of commonality and uniqueness seems to hold for existing developmental programs leading to space and ground-based applications of fission reactors.

If self-sustaining fusion reactors based on the D-He^3 (or possibly the D-D) reaction can be achieved, it is possible that fusion reactors will see their first large-scale applications in space, rather than for ground-based electrical power generation. Studies have shown that fusion reactors may be marginally competitive economically with other projected power generating systems (such as advanced fast-breeder reactors) on the ground (refs. 5 and 12), while mission analyses indicate that steady-state fusion reactors may be much superior to other competing space power and propulsion systems (ref. 8).

Some of the major research areas related to space applications that should receive attention are

1. A more detailed study of the D-He^3 reaction characteristics
2. The study of energy transport at the higher plasma temperatures involved
3. Systems studies of a D-D reactor, with loss of neutrons to space
4. Experimental and theoretical work on the conversion of the plasma energy to power or thrust
5. Studies of neutron and radiation shielding methods for superconducting coil protection
6. Development of lightweight, high-current-density superconducting magnets, lightweight cryoplants, and associated system components
7. Development of a liquid-metal ferrofluid suitable for space applications of magnetocaloric pumping and power generation
8. System and mission studies of space applications of pulsed fusion reactor concepts.

Work is also needed on methods of collecting the radially diffusing plasma from torodial systems and converting it into a unidirectional exhaust beam. One of the most important

unknowns, the space-restart system, cannot be adequately specified until controlled fusion has been achieved.

Lewis Research Center,
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